



Fermi National Accelerator Laboratory

FERMILAB-Conf-91/133

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May 1991

* Presented at the *14th Biennial IEEE Particle Accelerator Conference*, May 6 - 9, 1991,
San Francisco, CA.



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SUMMARY

A series of 16 high-gradient trim quadrupole magnets has been designed and built for the Tevatron luminosity upgrade (Fermilab III). These quadrupoles form part of the new Low-Beta system for the two interaction regions in the Tevatron Collider. The magnets have been installed in the Tevatron lattice in anticipation of the 1991 collider run.

The one-shell design uses a "cable" of individually insulated rectangular strands. The cable is overwrapped with Kapton and epoxy impregnated glass tape. The winding, curing and collaring of the magnet is accomplished in the same manner as Tevatron-like magnets using Rutherford style cable. Once the magnet is assembled, the five strands are connected in series to achieve high gradient at low current. The required gradient is 0.63 T/cm at 1086 A. The production magnets reached maximum currents of about 1.1 T/cm at 1990 A.

The success of this design approach suggests other applications in beam transport where magnets of high performance and low operating cost are required.

INTRODUCTION

The main arc magnets in a superconducting accelerator like the Tevatron are connected in series. A small number of power leads are used to feed current to the ring. Although the heat load of the power leads is high, it is small compared to other sources of heat in the magnet strings. Superconducting magnets used for correctors or trims, however, must be powered separately. The large number of these individually powered magnets can contribute a substantial fraction of the total heat load of the machine. The heat load of these leads can be reduced by designing magnets with as low a current as possible. The design of the Low-Beta system for the Fermilab Collider requires three high-gradient quadrupole trims on each side of the two interaction regions. These quadrupole trims replace standard correction packages in the existing spool pieces.

The design, described in detail in reference 1, features a single-shell coil wound with cable and copper wedges to approximate a $\cos 2\theta$ current distribution. The coil is supported by aluminum collars and surrounded by a laminated steel flux return yoke. The magnet cross section is shown in Figure 1.

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Requirements and specifications.

Aperture	3.00 inches
Maximum gradient	0.633 T/cm
Current	~1000 A
Maximum ramp rate	50 A/sec
Magnetic length	60.0 cm
Overall length	76.2 cm
Outside diameter	18.4 in.
Conductor alloy	NbTi
Cu:sc ratio	1.5:1
Number of filaments	612
Strand dimensions	1.09 x 1.75 mm ²
Cable dimensions	9.93 x 1.50 mm ²
Stored Energy	12,040 J/m at 1.1 kA
Inductance	19.9 mH/m

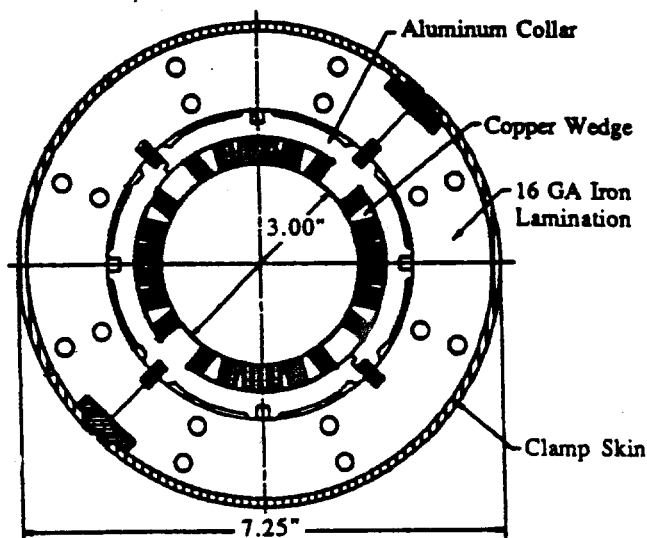


Figure 1. Magnet cross section.

The cable consists of five parallel monolithic conductors each individually Kapton wrapped. The five insulated strands are then overwrapped with the Kapton and epoxy/glass system first used on the Tevatron. The cable and insulation systems are shown in Figure 2.

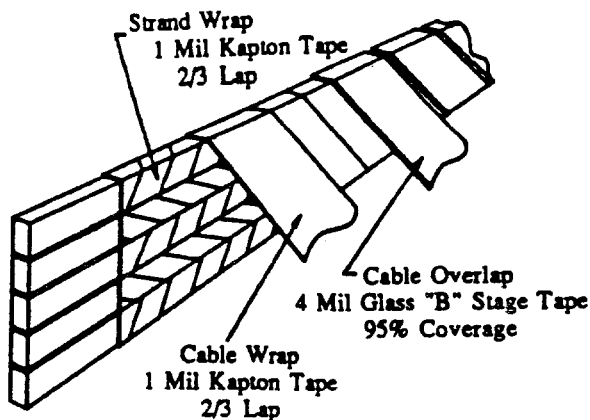


Figure 2. Cross and longitudinal sections.

Twelve spool pieces containing the quadrupole trims have been built and installed in the Tevatron ring. All of the magnets have been successfully operated in the ring during Low-Beta studies in the fall of 1990.

PRODUCTION EXPERIENCE

The construction techniques used in these magnets are described in reference 1. The fabrication methods are those traditionally employed in other accelerator quadrupoles using Rutherford style cable [2, 3]. This design approach is unique in that many splices are required to connect the cable strands.

Winding of coils using the five-strand cable presented no special problems. The ease of winding was attributable to the constant perimeter shape of the winding key ends.

Problems with the strand-to-strand cable splices became apparent after magnet operation in the test dewar. The magnet performance suggested high resistance joints. Disassembly of the affected magnets confirmed this data. Since room temperature resistance cannot be used to qualify the splices, additional rigor was imparted in the splice-making procedures along with modifications to the splice fixturing. The fixtures were modified to facilitate the addition of solder and maintain strand-to-strand pressure during the soldering operation. Subsequent assemblies using the revised techniques and tooling yielded magnets with the expected performance.

TESTING

Prior to cold testing, room temperature magnetic measurements were performed on each magnet to determine the field integral harmonics. All measured harmonics were found to be less than five units (at the 1 inch reference radius), except for the 12 pole which was measured to be approximately -16 units.

Next the magnet was tested in a vertical dewar of boiling liquid helium. Magnets were repeatedly quenched until a quench current plateau was established. The ramp rate for these quenches was 12 A/s. Each training quench exceeded the maximum operating current. Quenches were also performed at ramp rates up to 200 A/s. Magnets were deemed acceptable if they had a quench plateau current in excess of 1600 amps.

Magnets that failed this criterion invariably were found to have a poorly soldered splice joint.

For the first four cold tested magnets, body and integral magnetic measurements were also performed. These measurements were used to study the 12 pole versus current hysteresis, and to correlate cold harmonics with room temperature magnetic measurements.

Finally, the spool piece package containing the trim quadrupole and other correctors was cold tested at 4.6 K on a Tevatron test stand at the Fermilab Magnet Test Facility. The magnet was quenched once to verify that the magnet could reach the maximum operating current. In every case the magnet exceeded 1600 amps prior to quenching. Magnetic measurements were performed to determine the quadrupole field angle with respect to gravity and the magnetic center.

PERFORMANCE

For convenience, the conductor used for these magnets was derived from the same material used for the high-gradient quadrupoles built for the Low-Beta system [2, 3]. Although not optimum for the five-in-one magnet, the conductor performance was more than adequate. Some features of that conductor should be noted. Since the cross sectional area of the five-in-one strand is 8.7 times larger than the Low-Beta quadrupole strand, the filaments are 44 microns in diameter. Because of the nonoptimized drawing geometry and in particular the reduced strain ratio, the current density (~ 2000 A/mm², 4.2 K, 5T) is about a third less than the 0.528 mm strand used in the regular Low-Beta quadrupoles. There is no cabling degradation, however. Again the current density more than meets the requirement. Another unusual feature of this design is that the current density in the copper at the plateau is about 1450 A/mm² at short sample. This is to be compared with the copper current densities of about 1000 for other superconducting dipoles and quadrupoles.

Figure 3 shows the number of training quenches to plateau. The structure of the rectangular monolithic conductor is mechanically more stable than the Rutherford cable. This is reflected in the low training observed in these magnets in spite of the high-current densities.

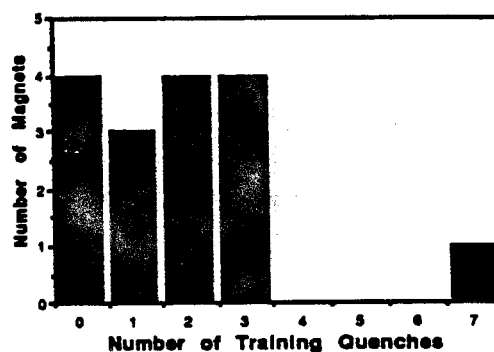


Figure 3. Number of training quenches.

Figure 4 shows the quench plateau current of each of the 16 quadrupoles that were built. Three of the magnets show plateaus somewhat below what is expected from conductor short sample measurement. This is attributable to a strand

with lower than normal short samples possibly due to damage during assembly. The lowest quench plateau is still 60% above the required current.

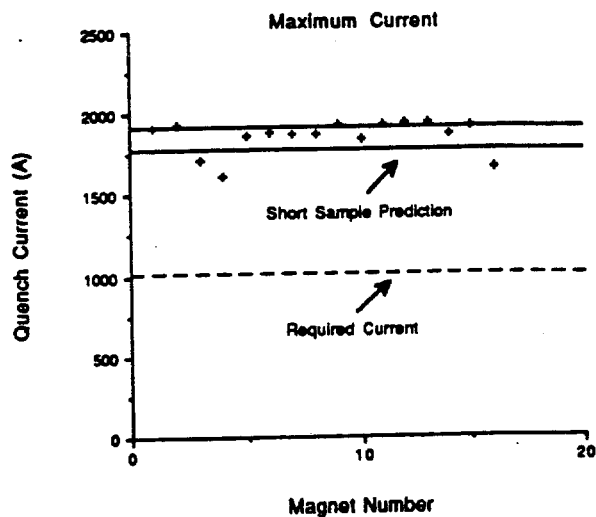


Figure 4. Quench plateau current.

The distribution in the first allowed multipole, the 12 pole, is shown in Figure 5. The approximately 16 units arise primarily from the ends. Although the ends were designed to be approximately 12 pole neutral, the fairly loose requirement on the 12 pole did not justify further refinement of the end geometry. Should 12 pole neutral ends be required on such a device, development of end geometries could be accomplished with the same techniques used for high-current, high-gradient quadrupoles.

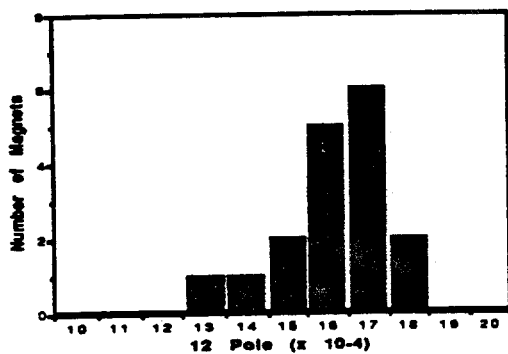


Figure 5. Twelve pole variation.

Ramp rate studies were done on all the magnets as part of the basic qualification procedure. Figure 6 shows a few examples of the ramp rate dependence for the Low-Beta single-shell quadrupole magnets. Most of the magnets reached the current expected from short sample measurements of the conductor. All of these magnets show the same rapid fall-off to quench current with increasing ramp rate as S5-001. However, an interesting phenomena occurs for those magnets which fell below the expected short sample limit (presumably due to conductor damage incurred either during processing or magnet construction). They maintain a plateau which

eventually meets the falling curve of the higher performance magnets. Note that the ramp rate is in amps/seconds in the strand. The cable current is a factor of five higher.

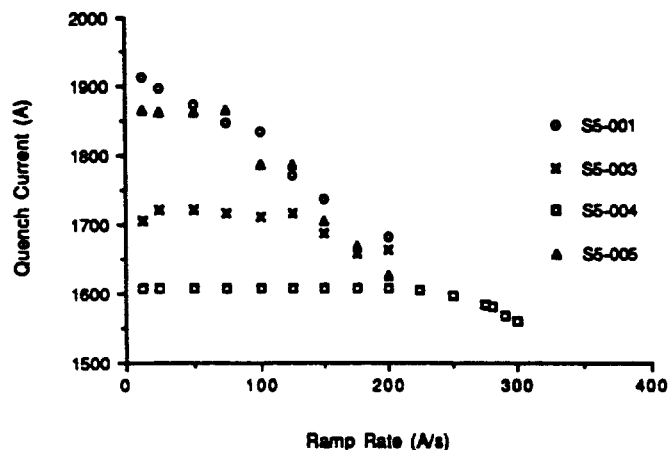


Figure 6. Ramp rate dependence of quench current.

CONCLUSIONS

Trim quadrupoles of a new design have been built, installed and tested in the Tevatron lattice as part of the Collider Low-Beta system. These high-gradient trims are a unique solution to the requirement for low-current individually powered magnetic elements. Beam transport systems between machines or to experimental areas pose the same requirements. Both quadrupoles and dipoles using this design could be built for that purpose.

REFERENCES

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